Robust maximum power point tracker using sliding mode controller for the three-phase grid-connected photovoltaic system

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Abstract

A robust maximum power point tracker (MPPT) using sliding mode controller for the three-phase grid-connected photovoltaic system has been proposed in this paper. Contrary to the previous controller, the proposed system consists of MPPT controller and current controller for tight regulation of the current. The proposed MPPT controller generates current reference directly from the solar array power information and the current controller uses the integral sliding mode for the tight control of current. The proposed system can prevent the current overshoot and provide optimal design for the system components. The structure of the proposed system is simple, and it shows robust tracking property against modeling uncertainties and parameter variations. Mathematical modeling is developed and the experimental results verify the validity of the proposed controller.

Keywords: Photovoltaic power systems; Sliding mode controller; Maximum power point tracker; MPPT

1. Introduction

Due to the depletion of fossil energy and environmental contamination, a renewable energy application such as photovoltaic (PV) system has been widely used for a few decades. The PV energy is free, abundant and distributed through the earth. Among the PV energy applications, they can be divided into two categories: one is stand-alone system and the other is grid-connected system. Stand-alone system requires the battery bank to store the PV energy which is suitable for low-power system. On the other hands, grid-connected system does not require the battery bank and has become the primary PV application for high power applications. The main purpose of the grid-connected system is to transfer maximum solar array energy into grid with a unity power factor.

The output power of PV cell is changed by environmental factors, such as illumination and temperature. Since the characteristic curve of a solar cell exhibits a nonlinear voltage–current characteristic, a controller named maximum power point tracker (MPPT) is required to match the solar cell power to the environmental changes. Many algorithms have been developed for tracking maximum power point of a solar cell (Eftichios et al., 2001; Valenciaga et al., 2001; Toshihiko et al., 2002; Hohm and Ropp, 2000). Among them, the most commonly used methods are perturb and observe (P&O) and incremental conductance algorithm. The P&O method measures the derivative of power (Δp) and the derivative of voltage (Δv) to determine the movement of the operating point. If the sign of (Δp/Δv) is positive, the reference voltage is increased by some amount of value or vice versa. The other method, the incremental conductance method can track the maximum power point voltage accurately than P&O method, by comparing the incremental conductance and instantaneous conductance of a PV array.
The typical configuration of a three-phase grid-connected photovoltaic system is shown in Fig. 1. It consists of solar array, input capacitor C, three-phase inverter, filter inductor L, and grid voltage $e_a$, $e_b$, $e_c$. The solar cells are connected in a series-parallel configuration to match the required solar voltage and power rating. The input capacitor supports the solar array voltage for a voltage source inverter. The three-phase inverter with filter inductor converts a DC input voltage into an AC sinusoidal voltage by means of appropriate switch signals to make the output current in phase with the utility voltage and obtain a unity power factor.

A typical controller configuration of the grid-connected photovoltaic system consists of MPPT controller, voltage controller and current controller as can be seen in Fig. 1 (Kotsopolos et al., 2001). The MPPT controller detects power slope from the solar array voltage and current information, and generates the reference voltage. The voltage controller adjusts solar array voltage to follow reference voltage using the proportional-integral (PI) controller in most cases. Thus, the output of the voltage controller becomes the current reference. The current controller controls inductor current to follow reference current using the hysteresis or predictive controller. The hysteresis controller has fast response time, but it has irregular switching frequency. Compared to the hysteresis, the predictive controller has constant switching frequency and good current control property, but it requires the exact information for circuit parameters. As current controller has cascade configuration with the voltage controller, the inductor current has overshoot if the reference voltage has been changed in a certain step. It is caused by the integrator of voltage controller. This current peak can stress the power device of inverter. The additional drawbacks of the conventional system are the tedious tuning for PI-gain selection and the requirement of the exact knowledge for circuit parameters.

The new controller has been proposed to overcome above problems in this paper. It consists of MPPT control-
rer and current controller only. The new MPPT controller generates power reference instead of voltage reference. This power reference is used for the current reference directly by the power balance relation. For the tight regulation of the inductor current, a sliding mode controller has been used for the current controller. The sliding mode controller has robust control property under the presence of parameter variations and can achieve the tight regulation of the states for all operating points (Domingo et al., 2001; Mauro and Mario, 1996; Liang et al., 2001). In this paper, an integral sliding mode controller for the three-phase photovoltaic system has been proposed. Due to the finite sampling time, there exists a steady-state error in the sliding mode controller. The integral sliding mode controller can eliminate the steady-state error by adding integral sliding surface. The mathematical modeling is evolved and the experimental result verifies the proposed controller.

2. Solar cell/array modeling

The voltage-current characteristic equation of a solar cell is composed of the light generated current source, diode, series resistance, and parallel resistance, which is described in Fig. 2(a). The terminal equation for the current and voltage of the solar cell is given as follows:

\[ I = I_{ph} - I_{sat} \left\{ \exp \left[ \frac{q}{AKT} (V + IR_s) \right] - 1 \right\} - \frac{V + IR_s}{R_{sh}} \]  

(1)

where \( I \) and \( V \) are the cell output current and voltage, and the definitions of the parameters are given in nomenclature.

The equivalent circuit for the solar cells arranged in \( N_p \)–parallel and \( N_s \)–series is shown in Fig. 2(b) and the mathematical equation for the array current and array voltage becomes as follows:

\[ I_{sa} = N_p I_{ph} - N_{p,sat} \left\{ \exp \left[ \frac{q}{AKT} \left( \frac{V_{sa}}{N_s} + \frac{I_{sa}R_s}{N_p} \right) \right] - 1 \right\} - \frac{N_p}{R_{sh}} \left( \frac{V_{sa}}{N_s} + \frac{I_{sa}R_s}{N_p} \right) \]

(2)

where \( N_p \) represents the number of parallel modules. Note that each module is composed of \( N_s \) cells connected in series. \( N_p I_{ph} \) corresponds to the short circuit current of the solar array. The characteristic curve of solar array as an example for \( I_{ph} = 2 \) A is shown in Fig. 6. The detailed parameters are shown in Table 1. These curves show a highly nonlinear characteristic around the maximum power point.

3. Modeling of the three-phase grid-connected photovoltaic system

The state-space model of a three-phase grid-connected photovoltaic system shown in Fig. 1 can be obtained by the dynamic equation described as follows:

\[ \begin{align*}
\dot{i}_a &= -\frac{R}{L} i_a - \frac{1}{L} e_a + \frac{V_{sa}}{3L} (2S_a - S_b - S_c) + \Delta f_1 \\
\dot{i}_b &= -\frac{R}{L} i_b - \frac{1}{L} e_b + \frac{V_{sa}}{3L} (-S_a + 2S_b - S_c) + \Delta f_2 \\
\dot{i}_c &= -\frac{R}{L} i_c - \frac{1}{L} e_c + \frac{V_{sa}}{3L} (-S_a - S_b + 2S_c) + \Delta f_3 \\
\dot{v}_{sa} &= \frac{1}{C} i_{sa} - \frac{1}{C} (i_a S_a + i_b S_b + i_c S_c) + \Delta f_4
\end{align*} \]  

(3)

where

\[ S_j = \begin{cases} 
1 & \rightarrow S_{jL} : \text{on,} \\
0 & \rightarrow S_{jL} : \text{off,} \\
0 & \rightarrow S_{jH} : \text{on,} \\
1 & \rightarrow S_{jH} : \text{off.}
\end{cases} \]

This model is nonlinear and time variant, but applying the \( \alpha, \beta \) transformation to (3), using an angular frequency of the grid line \( \omega \) rotating reference frame synchronized with the grids lines in which the d-component of the supply
The transformation matrix, nonlinear, can be written as

\[
\begin{bmatrix}
\frac{d i_d}{dt} \\
\frac{d i_q}{dt} \\
\frac{d e_s}{dt}
\end{bmatrix} = \begin{bmatrix}
\frac{-g}{t} & \omega & \frac{s_q}{t} \\
-\omega & \frac{-g}{t} & \frac{s_q}{t} \\
-\frac{s_q}{t} & -\frac{s_q}{t} & 0
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q \\
e_s
\end{bmatrix} \\
+ \begin{bmatrix}
-\frac{1}{2} & 0 & 0 \\
0 & -\frac{1}{2} & 0 \\
0 & 0 & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
e_d \\
e_q \\
e_s
\end{bmatrix} + \begin{bmatrix}
\Delta f_d \\
\Delta f_q \\
\Delta f_s
\end{bmatrix}
\]  (4)

where

\[
i_{qd} = K_{abc}^q \cdot i_{abc}, \quad e_{qd} = K_{abc}^q \cdot e_{abc},
\]

\[
\Delta f_{qd} = K_{abc}^q \cdot \Delta f_{abc}, \quad S_{qd} = K_{abc}^q \cdot S_{abc}
\]

The transformation matrix \( K_{abc}^q \) is given as

\[
K_{abc}^q = \frac{2}{3} \begin{pmatrix}
\cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\
\sin \theta & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ)
\end{pmatrix}
\]  (5)

The instantaneous power \( S \) which is delivered to the grid line is given as

\[
S = P + jQ
\]  (6)

where,

\[
P = \frac{3}{2} (e_d i_d + e_q i_q)
\]

\[
Q = \frac{3}{2} (e_d i_q - e_q i_d)
\]

where \( P \) is active power and \( Q \) is reactive power.

In synchronous D-Q rotating frame, \( e_d = 0 \). Therefore

\[
P = \frac{3}{2} e_q i_q
\]

\[
Q = \frac{3}{2} e_d i_q
\]  (7)

The active power \( P \) can be controlled by \( i_q \) current and reactive power \( Q \) can be controlled by \( i_d \) current.

4. Design of the integral sliding mode controller

The design of the sliding mode controller starts from the design of the sliding surface. Usually, the sliding surface is constructed by the linear combination of state variable errors which are defined as the differences between the state variables and their references. Therefore, in this case, the sliding surface can be designed with errors of the solar array voltage and inductor current in a three-phase grid-connected photovoltaic system. The reference solar array voltage is a DC voltage which is generated from the MPPT, but the solar array voltage is oscillating due to the unmatched circuit parameters, which results in an undesirable sliding mode performance.

The main purpose of a grid-connected photovoltaic system is to transfer the maximum solar array power into the grid with an unity power factor (Kasa et al., 2000). Therefore, the sliding surface should be designed to control the inductor current and solar array power simultaneously. This requirement can be achieved by selecting a sliding surface only using the errors of inductor current. If the reference inductor current is expressed as a function of the solar array power, then the sliding surface can control both the inductor current and solar array power simultaneously.

Assuming lossless power transmission between solar array and grid line, the following relationship is obtained from (7) if reactive power is controlled zero by setting \( i_{dref} = 0 \).

\[
P_{sa} = P_{grid} = \frac{3}{2} e_q i_q
\]  (8)

The proposed integral sliding surface is defined as follows:

\[
\sigma_1 = i_{dref} - i_d + c_1 \int_0^t (i_{dref} - i_d) dt
\]

\[
\sigma_2 = i_{qref} - i_q + c_2 \int_0^t (i_{qref} - i_q) dt
\]  (9)

where

\[
i_{qref} = \frac{2 P_{sa}}{3} e_q = \frac{2 P_{ref}}{3} e_q
\]

\[
i_{dref} = 0
\]

\( P_{ref} \) is the reference solar array power which is given by the MPPT controller.

The next step is to design a control input which satisfies the sliding mode existence law. The control input is defined as follows:

\[
v_d = S_d e_s, \quad v_q = S_q e_s
\]  (10)

The control input is chosen to have the structure as follows:

\[
v_d = v_{d_{eq}} + v_{nd}
\]

\[
v_q = v_{q_{eq}} + v_{nq}
\]  (11)

where \( v_{eq} \) is an equivalent control input that determines the system behavior on the sliding surface and \( v_{eq} \) is a nonlinear switching input which drives the state to the sliding surface and maintains the state on the sliding surface in the presence of the parameter variations and disturbances. The equivalent control input is obtained from the invariance condition and given by the following condition as

\[
\sigma_i = 0 \quad \text{and} \quad \sigma_{i} = 0 \Rightarrow v_i = v_{eq}
\]  (12)

Summarizing, the equivalent control input is given as

\[
v_{d_{eq}} = R_i i_d - \omega L_i e_d + e_d + c_1 L (i_{dref} - i_d)
\]

\[
v_{q_{eq}} = R_i i_q + \omega L_i e_d + e_q + c_2 L (i_{qref} - i_q)
\]  (13)

The nonlinear switching input \( v_{nl} \) can be chosen as follows:

\[
v_{nl} = k_i \cdot \text{sgn}(\sigma_i)
\]  (14)

If (13) and (14) are substituted into (11), the range of \( k_i \) ensuring \( \sigma_i \sigma_{i} < 0 \) can be determined as follows:
\( \sigma_1 \sigma_2 < 0 \)

\[
\sigma_1 \left( \frac{R}{L} i_d - \omega i_q + e_d + c_1 (i_{dref} - i_d) - \Delta f_d \right) - \frac{1}{L} (R i_d - \omega L i_q + e_d + c_1 L (i_{dref} - i_d) + k_1 \text{sgn}(\sigma_1)) < 0 \\
\sigma_1 \left( - \frac{k_1}{L} \text{sgn}(\sigma_1) - \Delta f_d \right) < 0
\]

\[
\sigma_2 \sigma_2 < 0
\]

\[
\sigma_2 \left( \frac{R}{L} i_q - \omega i_d + e_q + c_2 (i_{qref} - i_q) - \Delta f_q \right) - \frac{1}{L} (R i_q - \omega L i_d + e_q + c_2 L (i_{qref} - i_q) + k_2 \text{sgn}(\sigma_2)) < 0 \\
\sigma_2 \left( - \frac{k_2}{L} \text{sgn}(\sigma_2) - \Delta f_q \right) < 0
\]

Therefore, the ranges of the switching gains are given as follows:

\[
k_1 > \frac{L}{|\Delta f_d|} \\
k_2 > \frac{L}{|\Delta f_q|}
\]

From (13), (14) and (16), the control input \( v_i = v_{eq} + v_{mi} \) is given as follows:

\[
v_d = R i_d - \omega L i_q + e_d + c_1 L (i_{dref} - i_d) + k_1 \cdot \text{sgn}(\sigma_1) \\
v_q = R i_q + \omega L i_d + e_q + c_2 L (i_{qref} - i_q) + k_2 \cdot \text{sgn}(\sigma_2)
\]

\[
\begin{cases}
P_{\text{ref}} > P_{\text{sa avg}} \Rightarrow P_{\text{ref}} = \text{Hold previous value} \\ P_{\text{ref}} \leq P_{\text{sa avg}} \Rightarrow P_{\text{ref}} = P_{\text{ref}} + \Delta
\end{cases}
\]

where \( \Delta \) means a shift step from the previous value. The value of \( P_{\text{ref}} \) is reset periodically to compensate environmental changes of the solar array. The main advantage of this controller is that it does not require the measurement of the voltage derivative which can be a cause of divide-by-zero singularity problems.

Fig. 3 shows the proposed controller configuration. It consists of MPPT controller, sliding mode controller, and pulse width modulation (PWM) generator. The MPPT controller tracks the maximum power point using solar array voltage and current. The sliding mode controller controls the inductor current to follow the reference current by means of the sliding surface. The PWM generator generates the switching pattern according to the control input.

6. Simulation and experiment result

Fig. 4 shows the simulation result of the sliding mode controller using parameters shown in Table 1. The peak grid voltage \( e_q \) is set to 22.8 V and the frequency is 60 Hz. To verify the tracking performance of the proposed controller, \( P_{\text{ref}} \) is changed from 48 W to 96 W. This corresponds to the change of current reference \( i_{qref} \) from 1.4 A to 2.8 A. For the unity power factor transmission, the value of \( i_{dref} \) is set to zero. As can be seen in the figure, the \( i_q \) current exactly follows the \( i_{qref} \) for abrupt change of the value. As the solar array voltage corresponding 96 W is lower than the 48 W, the solar array voltage is changed from 69.4 V to 68.1 V.

To verify the performance of proposed controller in a three-phase grid-connected photovoltaic system, an experimental hardware has been setup as shown in Fig. 5. The DSP processor named TMS320C31-40 MHz is used to control sliding mode controller including MPPT algorithm. The sensor board collects analog signals for the control algorithm. The four-channel simultaneous sampling analog
to digital (A/D) converters are used for the analog sensor data acquisition. The FPGA is used for the PWM generation of each power switch. The PWM signals are applied to the gate driver of each switch. The four-channel digital to analog (D/A) converter is used to display control variables in oscilloscope. The control program is compiled in a PC and downloaded to the DSP via emulator. The software is executed at the interrupt routine that is called at every 0.1 ms.

The solar array simulator (SAS) has been used to simulate the photovoltaic array following the mathematical expression in (2). It consists of the adjustable current source and series connected diode string. This SAS can simulate the change in volt–current characteristics according to the temperature and illumination level variations by switching the value of current source and the number of series cells in a diode string. The measured volt–current characteristic for $I_{ph} = 2$ A is shown in Fig. 6. This curve is plotted from the Automated Test Equipment (ATE) which is connected to SAS by varying the resistance of ATE. The maximum power is 100 W and the maximum power point resides in 52 V. As the maximum output voltage is limited only to 63 V which is lower than the grid voltage, the inverter output is connected to the grid voltage through a step-up transformer in the experiment.

Fig. 7 shows the performance comparison between the conventional controller and the proposed controller when the reference value is step changed. As mentioned in the introduction, the conventional controller has overshoot in the $i_q$ current and it increases the current peak in the phase current. However, the proposed controller shows no overshoot and tight regulation property of the current control.

The $q$- and $d$-current waveform for a step change of $q$-reference is shown in Fig. 8. The $i_q$ current is exactly
Fig. 7. Comparison to the prior controller: (a) conventional controller and (b) proposed controller.

Fig. 8. Current waveform for a step change of $i_{qref}$ from 1.4 A to 2.8 A.

Fig. 9. Inductor current waveform for $I_{qref} = 2.8$ A.
controlled to the reference without overshoot when reference current has been changed. The $i_d$ current is controlled to zero even if the q-reference changed. This means that the power factor is controlled to one in any cases. The inductor current waveforms are shown in Fig. 9. There can be seen a distortion in the peak current waveform which is caused by the chattering characteristics of sliding mode control. The grid voltage and inductor current waveforms for a-phase are shown in Fig. 10. The phase voltage and current are synchronized and the unity power factor transmission is obtained. The frequency spectrum of the inductor current is shown in Fig. 11. The fundamental frequency is controlled to 60 Hz and the magnitude of third harmonic (180 Hz) or higher order harmonics are controlled at very low level. The sliding surface trajectories for the $P_{\text{ref}}$ change are shown in Fig. 12. The trajectory of $\sigma_1$ is always confined to sliding surface except for the reaching period. The trajectory of $\sigma_2$ is always controlled to sliding surface and it means the reactive power is always zero. The MPPT tracking performance of the proposed system is shown in Fig. 13. Due to the ripple in the solar array voltage, the average value was used for the calculation of solar array power $P_{\text{sa}}$. The power reference $P_{\text{ref}}$ is generated from (18) using average value. The displayed value of $P_{\text{ref}}$ is the one-step delayed value of the algorithm. As can be seen in the figure, the solar array power $P_{\text{sa}}$ follows the reference value $P_{\text{ref}}$ until maximum power point is attained. Above the maximum power point, the $P_{\text{sa}}$ cannot follow the refer-

Fig. 10. Grid voltage and inductor current waveform for a-phase.

Fig. 11. Frequency spectrum of the inductor current.
ence value and the reference value returns back to previous value. The solar array voltage is controlled to the 54 V which is corresponds to the near peak power voltage in Fig. 6.

7. Conclusions

A robust maximum power point tracker using sliding mode controller for the three-phase grid-connected photovoltaic system has been proposed. The proposed system consists of a new MPPT controller and current controller. The current reference is directly generated from the MPPT. The integral sliding mode controller is used as a current controller for the tight regulation of the inductor current. The proposed system can avoid current overshoot and make an optimal design of power devices. The proposed system is simple and shows superior performance under parameter variation environments.

References


